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Publication date:
2016

Document Version
Peer reviewed version

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Citation (APA):

Burlina, C., Georgakis, C. T., Larsen, S. V., & Egger, P. (2016). Optimization of bridge cables with concave fillets. Paper presented at 8th International Colloquium on Bluff Body Aerodynamics and Applications, Boston, United States.

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Optimization of bridge cables with concave fillets

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SUMMARY:

In this paper the aerodynamic performance of new cable surfaces with concave fillet are examined and compared to plain, dimpled and helically filleted surfaces. To this end, an extensive wind-tunnel campaign was undertaken. Preliminary flow visualizations tests and static tests were performed to better understand the structure and development of the wake and the related aerodynamic forces. Subsequent improvements in design were focused on drag reduction and rain rivulet suppression. For this purpose a number of samples with different concave fillet's height were tested in static condition to estimate the aerodynamic forces. Both new cable surfaces outperform traditional surfaces in terms of rain-rivulet suppression thanks to the ability of the concave shape of the fillet to act as a ramp for the incoming rain-rivulet. Furthermore, both improved innovations with lowest height of the concave fillet show optimal drag coefficients in the supercritical Reynolds range and an early suppression of vortex shedding formation.

Keywords: cable aerodynamics, concave fillets, rain rivulet suppression, flow visualizations, static forces.

1. INTRODUCTION

In order to reduce wind-induced vibrations on bridge stay cables, such as rain wind induced vibrations (RWIV) and dry galloping, bridge cable manufacturers have introduced surface cable modifications on high-density polyethylene (HDPE) pipes. These modifications come mainly in the form of helical fillets, extensively used in Europe and America, and in the form of dimples, used mainly in Asia. The main purpose of these modifications is rain-rivulet impedance, since the presence of one or more longitudinally running rivulets on the cable surface is considered one of the major causes of the initiation of wind-induced vibrations. Nevertheless, the introduction of helical fillets and dimples has not completely eliminated RWIVs, often leading bridge owners to the installation of cable vibration dampers or cross-ties (Kleissl and Georgakis, 2013). Previous research (Yagi, 2011 and Kleissl and Georgakis, 2013) shows that by modifying the shape, alignment and configuration of the protuberances on the HDPE tube, it is possible to eliminate or further reduce the RWIVs, together with a reduction in drag force. Drag force represents more than 50% of the overall horizontal wind load on long span bridges (Gimsing and Georgakis, 2012). In particular modifications in the form of a concave fillet, studied by Kleissl and Georgakis (2013), were found to outperform traditional surfaces, showing similar aerodynamic coefficients, compared to a traditional helical fillet and dimpled surface despite a significant increase in the fillet height.

As a result, the objective of the present study is to examine and optimize the aerodynamic performance and to further understand the behavior of innovative bridge cable surfaces with concave fillet, compared with plain, dimpled and helically filleted surfaces. In particular a better understating of the structure and development of the near-wake of bridge cables make it possible to employ further manipulation and improvement of the concave fillet for drag reduction, while at the same time

guaranteeing optimal performances in terms of rain-rivulet suppression.

To this end, an extensive wind-tunnel test campaign was performed at the Climatic Wind Tunnel (CWT) at FORCE Technology (Denmark). Preliminary flow visualization tests and static tests were performed in order to understand the development of the near wake and its dependency to the aerodynamic forces. In a second stage a parametric investigation was undertaken. Different samples with different concave fillet height were tested and compared to the traditional surfaces in terms of aerodynamic forces and rain-rivulet suppression. This investigation was performed in order to understand the dependencies of the height and the radius of the concave fillet on the suppression of the rain-rivulet and on the development of the wake in relation to the resultant drag coefficient.

Furthermore, it is hypothesized that an increase height of the fillet in the innovation with the staggered surface will be able to retain the snow and ice longer and then subsequently allow the melted accretions to fall from cables in smaller, less hazardous pieces, while maintaining the same low level of drag coefficient compared to the lower fillet height and different surface modifications available. Numerous bridges around the world have begun to report snow and ice accretion related operational issues and closures. A particular case was reported in December 2012, where severe cable snow accretion led to the closure of the Port Mann Bridge in Canada (CBC News, British Columbia, 2012). Numerous cars were damaged and several people were injured due to falling snow from bridge cables. Snow and ice accretions on bridge cables have become increasingly problematic for the safe operation of the bridge and the lifetime of the cables.

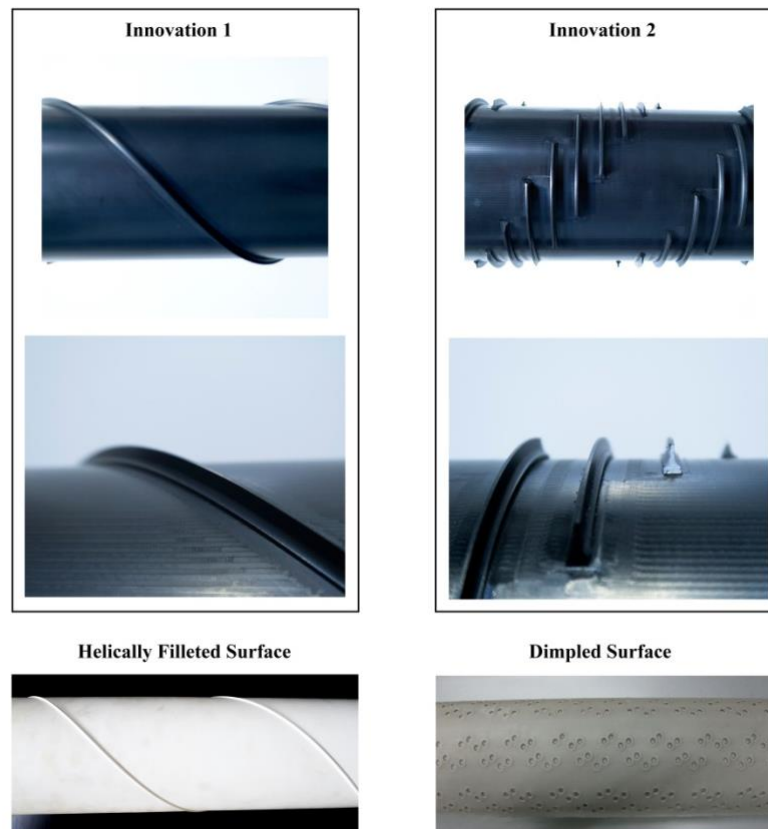


Figure 1. Cable samples models

2. MODELS

The models tested were full-scale samples of high density polyethylene (HDPE) tubing, with an outer diameter of 160mm (excluding fillets). Different cable surfaces were tested (Figure 1). Two innovative profiles that involve the application of concave protruding fillets were tested. The fillets have a $3.14 \times$ tube diameter pitch length, which results in a 45° pitch angle and a spiral distance of 251mm. The fillet cross section has a trapezoidal shape with concave sides. In the first model, which subsequently be referred to as Innovation 1, the fillets replicate the typical arrangement of current stay cables with helical fillets, which consists in a 45° pitch angle and a spiral distance of 251mm. In the second model, Innovation 2, the fillets are arranged laterally in a staggered helical pattern with a pitch angle of 30° and spacing between the fillets of 20mm. For both innovations three different height of the fillet were produced and tested after a preliminary analysis of the wake development and aerodynamic forces. For comparison purposes also a plain, dimpled and traditional helically filleted surface were tested.

3. EXPERIMENTAL WORK

The cables section prototypes were placed horizontally in the wind tunnel cross section, resulting in a near two-dimensional flow normal to the cable section, for both static and flow visualization set-ups. The drag and lift forces were measured up to super-critical Reynolds number range, using 6DOF force transducers (AMTI MC3A-500) at either end. The two force transducers were installed between the cable model and supporting cardan joints. The length of the models was 1.52m. The blockage ratio for the cable model ratio for the cable model was 8% and thus the drag coefficients have been corrected using the Maskel III method, according to Cooper et al. (1999). For each tested configuration, the drag C_D and the lift C_L coefficients were calculate, based on the averaged along-wind and across-wind forces respectively, and normalized by the along-wind flow velocity:

$$C_D = \frac{F_D}{\frac{1}{2}\rho U^2 L D} \quad (1)$$

$$C_L = \frac{F_L}{\frac{1}{2}\rho U^2 L D} \quad (2)$$

where F_D is the along-wind force and F_L is the across-wind component, U is the mean wind velocity, L is the effective length of the cable, D the outer diameter and ρ the air density, taken here as 1.25kg/m^3 .

During the flow visualization tests, smoke particles were added into the flow to trace the fluid motion. With smoke particles in the order of $0.2\mu\text{m}$, it can be assumed that the particles follow the streamline of the flow. Due to dispersion of the particles at high wind velocities, tests were run up to the sub-critical Reynolds number range limit. In order to visualize a slice of the fluid flow pattern, the particles were illuminated with sheet of laser light.

Rivulet suppression tests were performed with the cable declining along the wind direction at a relative cable-wind angle of 45° (See Kleissl and Georgakis 2013). A plain surface cable section was used to make up the first top half of the model length, in order to facilitate the formation of the upper and lower rivulet, while the different cable surfaces section were used to make up the second half of the model length. All tests were repeated for 8m/s and 14m/s, which are the representative values for the upper and lower velocity range for RWIV.

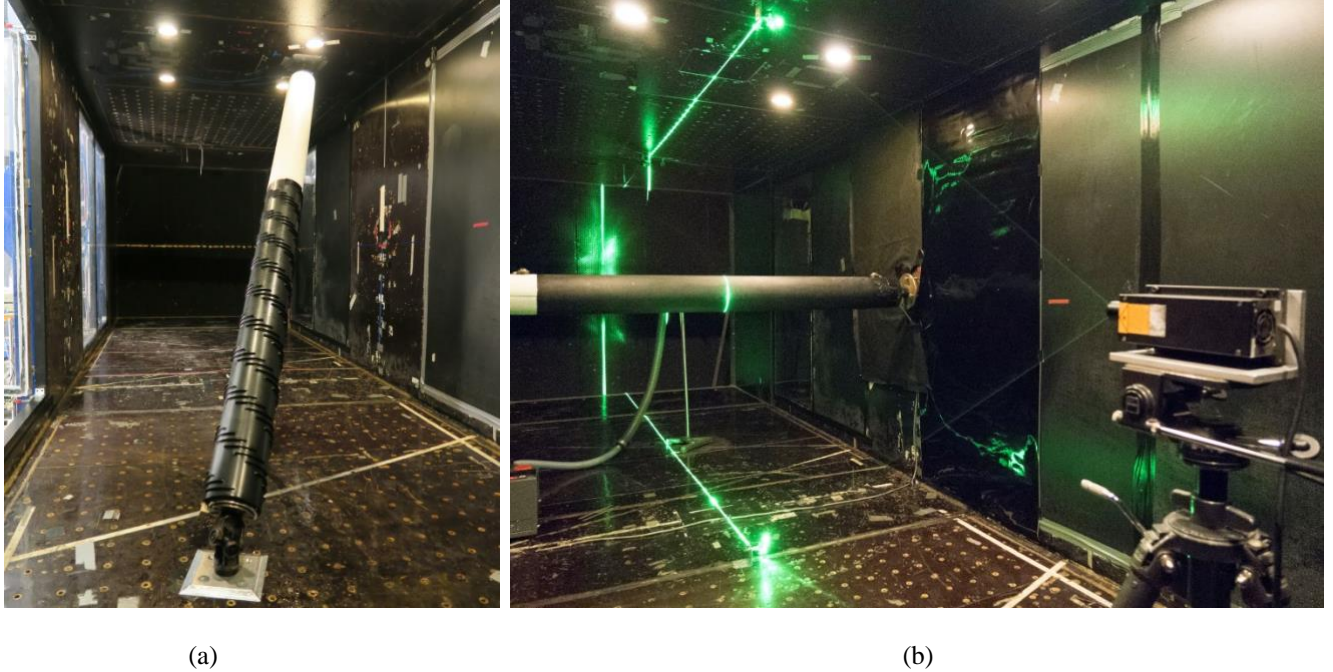


Figure 2. Rivulet suppression Set-up (a) and Static and Flow Visualization Set-Up (b)

4. RESULTS AND DISCUSSION

4.1 Flow visualization

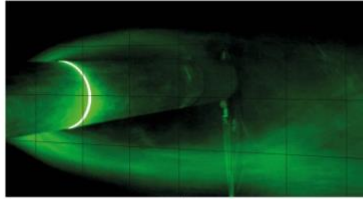
Flow visualization tests were performed on the original designs of Innovation 1 and 2 with a concave fillet height of 6.9mm and compared with a plain, dimpled cable surface and a traditional helically filleted cable surface with a fillet height of 2mm. The flow visualizations of the near-wake and separation mechanisms are shown in Figure 3. The near-wake photographs represent the average wake size over a full development and evolution of its structure.

From $Re = 0.6 \times 10^5$ to $Re = 1.5 \times 10^5$ all five samples exhibit a reduced width of their wakes, indicating also a drop in the drag coefficient. When comparing them, this behaviour is particularly enhanced for the dimpled surface and Innovation 2. As we can see from Figure 3, both this last two cable surfaces exhibit the same separation mechanism of a plain cable in the supercritical state, where the boundary layer is fully turbulent before the separation line, resulting in a narrower wake and in a drop of the drag coefficient (Zdravkovich, 1997). This mechanism is generated artificially by the dimples in the dimpled surface and by the staggered concave fillets in Innovation 2, which are able to initiate turbulence at the boundary layer at low Reynolds numbers with an early transition to the post-critical state (Burlina et al., 2016). It is hypothesized that an increase or decrease of the concave fillet height in Innovation 2 will not affect the performance in terms of drag force, thanks to the enhanced turbulence at the boundary layer at low Reynolds number.

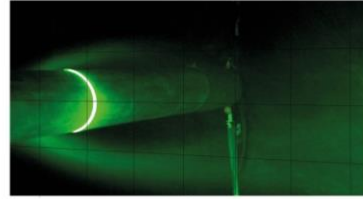
On the other hand, Innovation 1, exhibit a smaller reduction in the wake size and a resulting higher drag coefficient, compared to the other surfaces. The flow is governed by the presence of the concave fillet which acts as a ramp for the incoming flow, creating a fixed separation point a subsequent enhanced vorticity. This particular behaviour does not allow for a transition in the flow for increased Reynolds numbers, leading to a small reduction of the wake's size and subsequently a small reduction

of the drag coefficient also in the supercritical range. It is hypothesized that a reduction of the height of the concave fillet will result in a narrower wake and a as a consequence a lower drag, whilst maintaining optimal performance in terms of rain-rivulet suppression (Burlina et al., 2016).

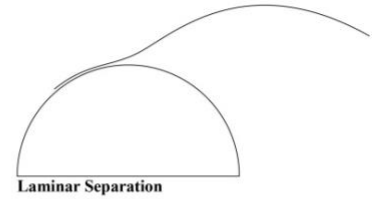
Plain Surface



$Re = 0.6 \times 10^5$ $C_D = 1.06$

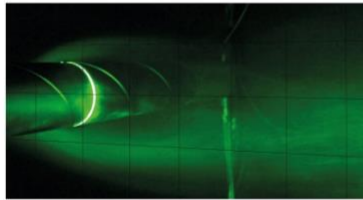


$Re = 1.5 \times 10^5$ $C_D = 0.88$

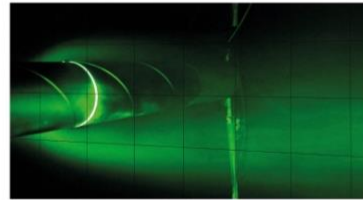


Laminar Separation

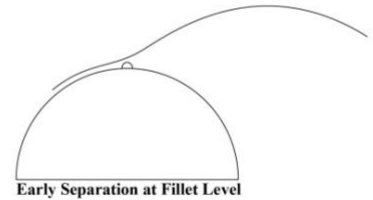
Helically Filleted Surface - 2mm fillet



$Re = 0.6 \times 10^5$ $C_D = 1.05$

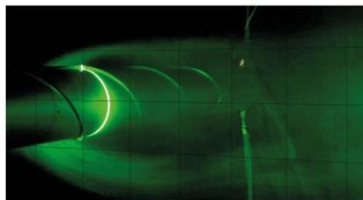


$Re = 1.5 \times 10^5$ $C_D = 0.88$

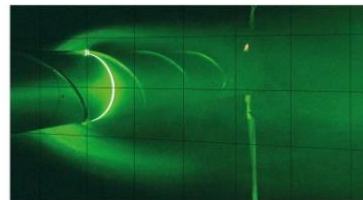


Early Separation at Fillet Level

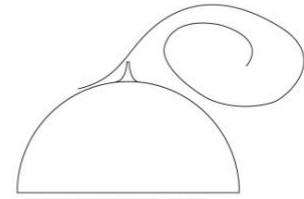
Innovation 1 - 6.9mm fillet



$Re = 0.6 \times 10^5$ $C_D = 1.05$

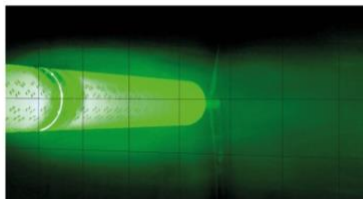


$Re = 1.5 \times 10^5$ $C_D = 0.87$

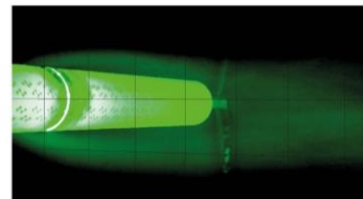


Separation at Fillet Level
Enhanced Vorticity after Separation

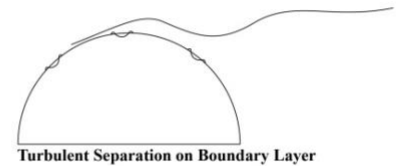
Dimpled Surface



$Re = 0.6 \times 10^5$ $C_D = 1.15$

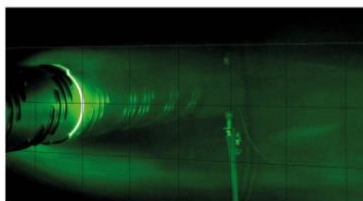


$Re = 1.5 \times 10^5$ $C_D = 0.72$

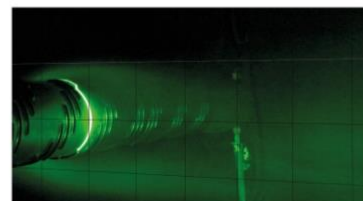


Turbulent Separation on Boundary Layer

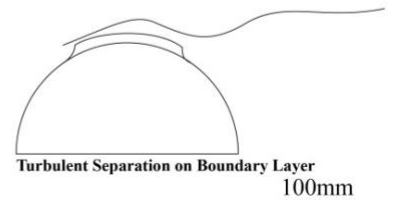
Innovation 2 - 6.9mm fillet



$Re = 0.6 \times 10^5$ $C_D = 1.00$



$Re = 1.5 \times 10^5$ $C_D = 0.70$



Turbulent Separation on Boundary Layer

100mm

Figure 3. Near flow visualization for different cable surfaces at $Re=0.6 \times 10^5$ and $Re=1.5 \times 10^5$

4.2 Force coefficients

A parametric investigation was performed on a set of the two innovations' samples in order to understand the dependencies of the variation of the concave fillet height in terms of aerodynamic forces. Furthermore, they were compared with the plain, dimpled and helically filleted surface.

It can be noted in Figure 4a that for Innovation 1 a decrease of the fillet height from 6.9mm to 4.3mm results in a decrease of the drag coefficients in the supercritical range from 0.76 down to 0.71. When compared to the helically filleted surface (Figure 4c), Innovation 1 with the 4.3mm concave fillet height experiences the same drag force compared to the traditional helical fillet with the 4mm fillet height, while the helically filleted surface with the 2mm fillet height experiences a lower drag of 0.64 when entering the post-critical range. This is due to a more accentuated drag transition in the Reynolds number range between 2.0 and 2.6×10^5 . Despite the same arrangement of the fillet for the surfaces in question, the higher drag coefficient in the post-critical Reynolds range for Innovation 1 can be attributed to the higher profile of the fillet directly facing the incoming flow, which acts as a fixed ramp and separation point and thus resulting in a wider wake. This phenomenon is anyway reduced when reducing the concave fillet height from the one used in its original design.

On the other hand, Innovation 2 (Figure 4b) shows the same level of drag force of approximately 0.65, when either increasing the concave fillet height up to 8.3mm or decreasing it down to 4.3mm. As stated earlier, it is believed, that this optimal performance is due to the ability of the staggered sharp shaped concave fillet facing the flow, to enhance vorticities at the boundary layer resulting in a narrower wake and subsequent lower drag. Furthermore, when compared to the other surface technologies (Figure 4d), Innovation 2 and the dimpled surface show an earlier reduction in the drag force in the sub-critical Reynolds range and exhibit a more smooth and prolonged transition which starts at a lower Reynolds number between $0.8 - 1.0 \times 10^5$ and enters the post-critical state at a Reynolds number of 2.0×10^5 . The early flow transition for the dimpled surface cable agrees well with what has been observed for circular cylinders with uniform high roughness, which easily triggers turbulence ensuring a near constant super-critical drag (Miyata et al. 1994 and Hojo et al. 1995). For Innovation 2, it is hypothesized that the early transition and the subsequent constant super-critical drag is the result of the fact that the circumferential orientation of the fillets reduces the drag penalty, whilst triggering turbulence at the boundary layer and introducing counter rotating vortices (Burlina et al., 2016). Subsequently, as previously stated, it is hypothesized that the higher concave fillet of 8.3mm can allow a longer retention of the snow and ice and then can allow the melted accretions to fall from cables in smaller, less hazardous pieces, while been able to maintain the a low level of drag coefficient.

Concerning the lift force, apart from the plain cable surface as mentioned before, the other four cable surfaces experience an almost zero lift along the whole range of wind velocities tested (Figure 4f). This is most likely due to the ability of all the surface modifications to generate variations in the flow and separation lines along the length of the cable. These variations, as largely reported in previous studies, are the result of enhanced vorticities and counter rotated vortices for the dimpled surface (Miyata et al., 1994) and of periodic structures in the spanwise direction with localized increased streamwise vorticities and elongations of the vortex formation region for the traditional helical fillet (Nebres and Batill, 1993). Innovation 1 and 2 are also able to suppress vortex shedding formation at lower Reynolds numbers compared to the dimpled and traditional helically filleted cable surfaces, which maintain it up to the critical Reynolds number range (Burlina et al., 2016).

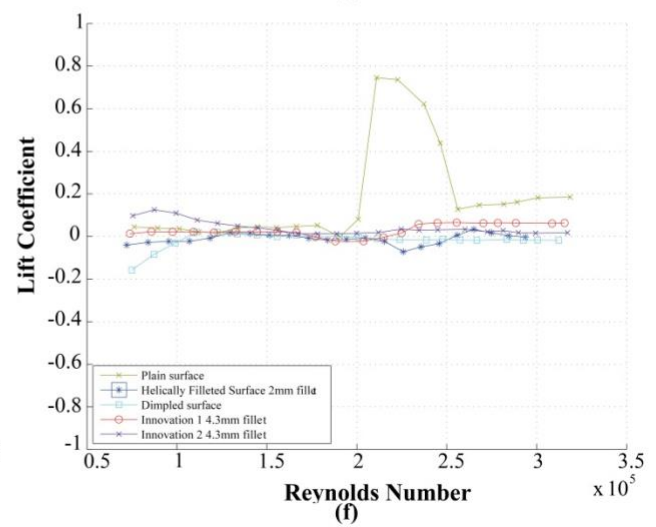
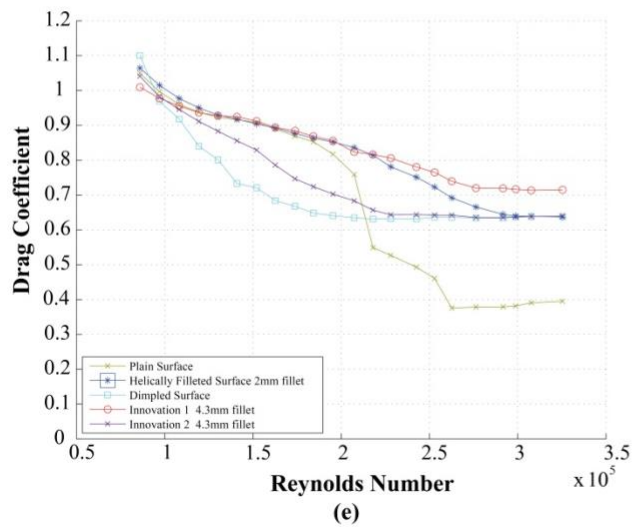
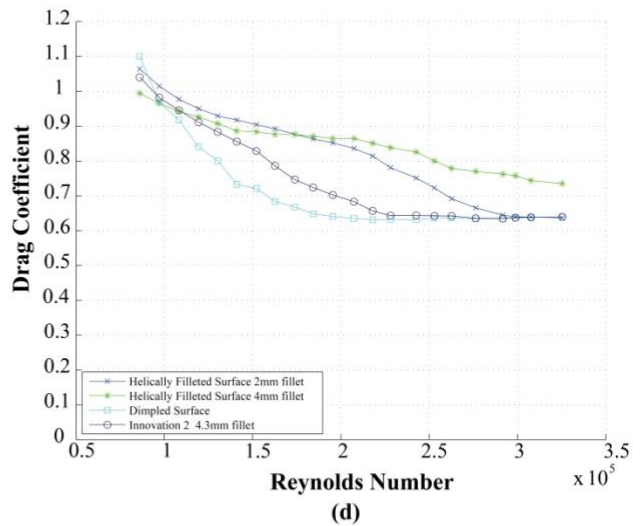
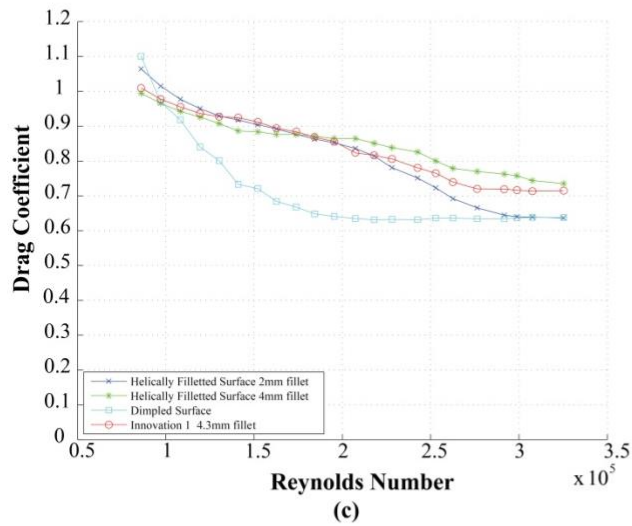
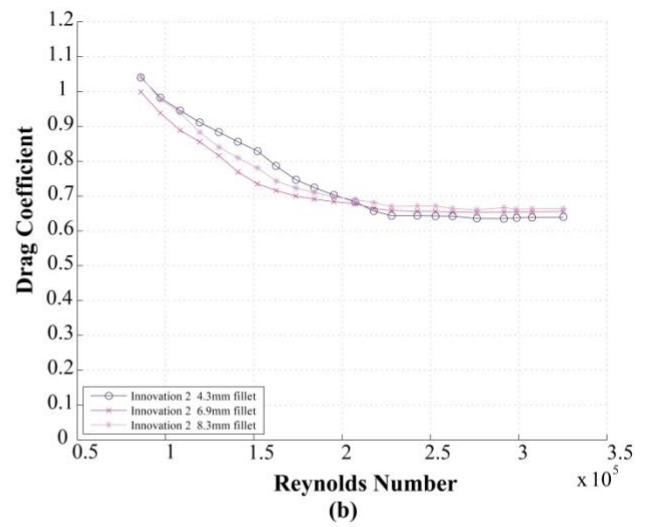
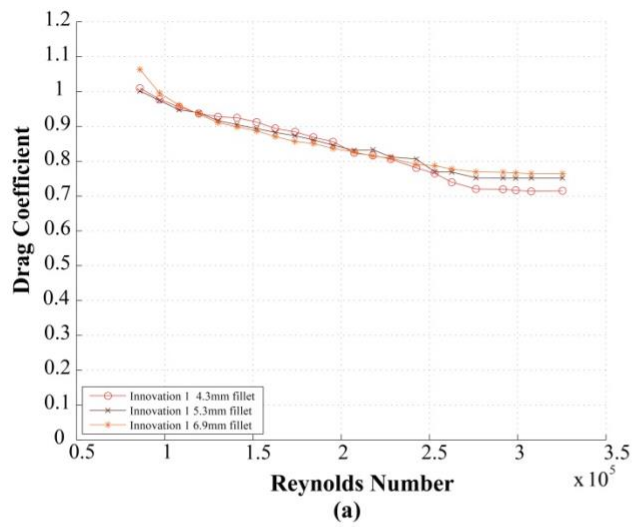


Figure 4. Force coefficients for different cable surfaces

4.3 Rivulet suppression

As found in previous studies by Kleissl and Georgakis (2013) the critical range of velocities for the formation of both upper and lower rain-rivulet is between 7 – 15m/s. Outside this range, the upper rivulet does not form, as either gravity or the wind loading become dominant. As RWIVs typically occur within this range, the presence of the upper rivulet is considered particularly critical for the initiation of these vibrations.

Figure 5 shows the rain rivulet suppression ability of the tested cable surfaces. The helically filleted surface for both the different fillet height of 2mm and 4mm is able to reduce the size of the rain rivulet along the length of the cable but it is not able to completely suppress it. On the other hand, Innovation 1 and Innovation 2 experience a complete suppression of the upper and lower rivulets at both wind velocities tested. The particular shape of the concave fillet acts as a ramp, blocking the formation of the upper and lower rivulet along the whole length of the cable. It was noted that this is mainly due to the concavity of the fillet and its sharp top edge.

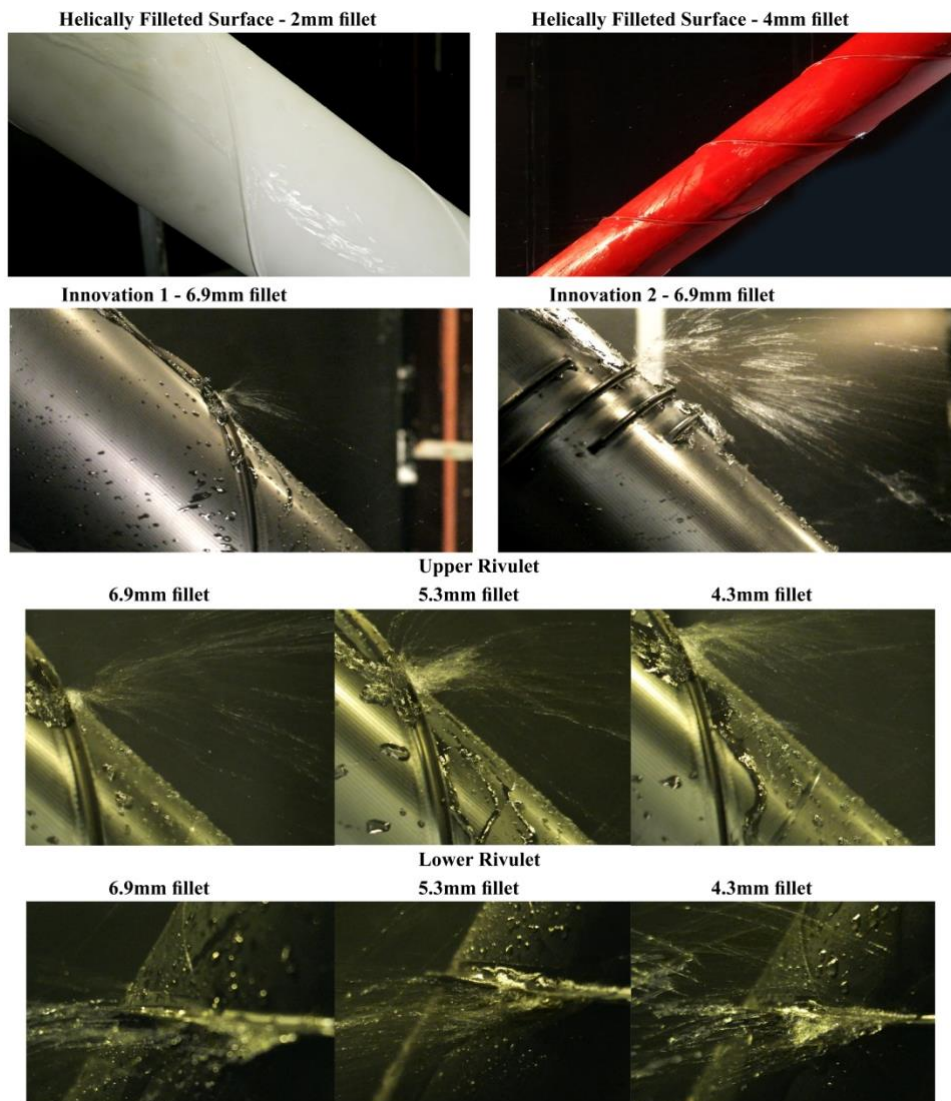


Figure 5. Rivulet suppression ability for different cable surfaces

Furthermore, the concave fillet is able to outperform also at the lowest height of 4.3mm. It shows an almost complete suppression of the upper and lower rivulet at all velocities tested, while been able to improve the performance in terms of aerodynamic forces with a reduction of the drag force as previously analysed.

4. CONCLUSION

Two new cable surfaces with concave fillets were wind tunnel tested for the determination of the aerodynamic coefficients, the structure of the flow's near wake and for rain-rivulet suppression. The results were compared with plain, dimpled and helically filleted surfaces. Furthermore, a parametric investigation was performed on the concave fillet shape in order to improve its performance.

Innovation 1 and 2 outperformed in terms of rain-rivulet suppression, with a suppression of the upper and lower rain-rivulets at all tested velocities also for the lower profile of the concave fillet tested. This is due to the ability of the concave fillet to act as a ramp for the incoming rain-rivulet.

Both innovations maintain optimal performances in terms of aerodynamic coefficients. In particular, Innovation 2 exhibit the same behaviour as a dimpled cable surface in terms of drag coefficient, showing an early transition to the supercritical range and a subsequent reduction of the drag force. This is due to the ability of the staggered surface configuration to enhance turbulence at the boundary layer level. Innovation 2 is also able to suppress vortex shedding formation at lower Reynolds numbers compared to the dimpled cable surface, which maintains it up to the critical Reynolds number range (Burlina et al., 2016). Furthermore, Innovation 2 is able to maintain a low level of drag force even with an increase of the height of the concave fillet from its original design, which results in more than 100% increase of the fillet compared to a traditional helical fillet. It is hypothesized that an higher concave fillet can allow a longer retention of the snow and ice and then can allow the melted accretions to fall from cables in smaller, less hazardous pieces.

On the other hand, Innovation 1 shows a higher drag in the super-critical range compared to Innovation 2. This is due to the helical arrangement of the concave fillet, which act as a fixed ramp and separation point and thus resulting in a wider wake. This phenomenon is anyway reduced when reducing the height of the fillet while maintaining optimal performance in terms of aerodynamic forces.

ACKNOWLEDGEMENTS

This work would not have been possible without the generous support of VSL International and FORCE Technology.

REFERENCES

- Burlina, C., Georgakis, C.T., Larsen, S.V., Egger, P., 2016. Comparative analysis of bridge cables with concave fillets. Proceeding of The first International Symposium on Flutter and its Application (ISFA2016), Tokyo, Japan.
- Cooper, K., Mercke, E., Wiedemann, J. 1999. Improved blockage corrections for bluff-bodies in closed and open wind tunnels, In: 10th International Conference Wind Engineering, Copenhagen, June., pp. 1627-1634.
- Flamand, O., 1995. Rain-wind induced vibration of cable, In: J. of Wind Engineering and Industrial Aerodynamics, 57 (2-3), 353-340.
- Flamand, O., Boujard, O., 2009. A comparison between dry cylinder galloping and rain-wind induced excitation, In: Proceeding of the 5th European & African Conference on Wind Engineering, Florence.
- Georgakis, C.T., Koss, H.H., Ricciardelli, F., 2009. Design specifications for a novel climatic wind tunnel for the testing of structural cables, In: 8th International Symposium on Cable Dynamics, Paris, France, September, pp. 333-340.
- Gimsing, N.J., Georgakis, C.T., 2011. Cable Supported Bridges: Concept and Design, 3rd ed. John Wiley & Sons Ltd.

- Hojo, T., Yamazaki, S., Okada, H., 2000. Development of Lowdrag Aerodynamically Stable Cable with Indented Processing, Nippon Steel Corporation, July (Special Issue on Steel Structure 82), URL <http://www.nsc.co.jp/en/tech/report/pdf/8203.pdf>.
- Hojo, T., Yamazaki, S., Miyata, T., Yamada, H., 1995. Development of aerodynamically stable cables for cable-stayed bridges having low resistance, *Bridges & Foundations Engineering* 6, 27–32, in Japanese,
- Kleissl, K., Georgakis, C.T., 2011. Comparison of the aerodynamics of bridge cables with helical fillets and a pattern-indented surface in normal flow (a), In: *Proceedings of the 13th International Conference on Wind Engineering*, Amsterdam, Netherland.
- Kleissl, K., Georgakis, C.T., 2011. Comparison of the aerodynamics of yawed bridge cables with helical fillets and a pattern-indented surface (b), In: *Proceedings of the 9th International Symposium on Cable Dynamics*, Shanghai, China.
- Matsumoto, M., 1998. Observed behavior of proto type cable vibration and its generation mechanism, In: *Bridge Aerodynamics, Proceedings of the International Symposium on Advances in Bridge Aerodynamics*, pp. 189–211.
- Matsumoto, M., Daito, Y., Kanamura, T., Shigemura, Y., Sakuma, S., Ishizaki, H., 1998. Wind-induced vibration of cables of cable-stayed bridges, In: *J. of Wind Engineering and Industrial Aerodynamics*, 74-76, 1015 – 1027.
- Miyata, Y., Yamada, H., Hojo, T., 1994. Experimental study on aerodynamic characteristics of cables with patterned surface, In: *J. of Structural Engineering* 40A (March), 1065–1076.
- Miyata, T., Katsuchi, H., Tamura, Y., 1999. Comprehensive discussion on structural control for wind-induced responses of bridges and buildings, In: *Wind Engineering into the 21st Century, Proceedings of the 10th International Conference on Wind Engineering*, vol. 1, pp. 487–494.
- Nebres, J. V., Batill, S. M., 1992. Flow about cylinders with helical surface protrusions, In: *30th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, Nevada 92 (0540).
- Yagi, T., Okamoto, K., Skski, I., Koroyasu, H., Liang, Z., Narita, S., Shirato, H., 2010. Drag force reduction and aerodynamic stabilization of stay cables by modifying surface configurations, In: *The 21th Symposium on Wind Engineering*, Tokyo, Japan. In Japanese.
- Zdravkovich, M. M., 1981. Review and classification of various aerodynamic and hydrodynamic means for suppressing vortex shedding, In: *Journal of Wind Engineering and Industrial Aerodynamics* 7 (2), 145 – 189.
- Zdravkovich, M. M., 1984. Reduction of effectiveness of means for suppressing wind-induced oscillation, In: *Engineering Structures* 6 (4), 344 – 349.
- Zdravkovich, M. M., 1997. *Flow around circular cylinders vol.1: fundamentals*, Oxford Science Publications, 1997.
- CBC News, British Columbia, 2012. “Port Mann Bridge closure unacceptable, says minister.” <http://www.cbc.ca/news/canada/british-columbia/story/2012/12/20/bc-port-mann-ice.html> (Dec. 20, 2012)